

Driving mechanism in massive B-type pulsators

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Abstract

After a historical introduction, I present the current status of our understanding of the mechanism responsible for pulsation in β Cephei and SPB stars.

Introduction

Variability of the certain β Cephei stars has been known since the beginning of previous century but serious efforts to explain its origin were undertaken much later. To my knowledge Paul Ledoux was the first theorist who got interested in these objects and the first who invoked nonradial oscillations to explain pulsation in any stars. In his pioneering work, Ledoux (1951) used data on spectral line profile changes to reveal nature of modes responsible for variability of prototype star with two close frequencies. More than ten years later, Chandrasekhar & Lebovitz (1962) proposed a different interpretation of the two frequencies. These two papers had a lasting impact on studies of nonradial oscillations in stars. However, the matter of driving was only briefly touched upon. The search for the driving mechanism began few years after. There has been a number of proposals suggesting the deep interior as the site of the driving effect. As it turned out, this was not correct.

The road toward correct answer was initiated by Stellingwerf (1978). He noted that a slight bump in opacity connected with the HeII ionization edge at $T = 1.5 \times 10^5 \text{K}$ produces a substantial driving effect in β Cep models. The effect was not big enough to cause an instability of any mode in any of the models. However, Stellingwerf suggested that an improvement in the opacity calculations might lead to an enhancement of the bump and consequently to instability of modes corresponding to β Cep pulsations. Subsequently, Simon (1982) pointed out that augmenting the heavy element opacities by the 2–3

factor would resolve the period ratio discrepancy in classical Cepheid, which has been another outstanding puzzle in stellar pulsation theory, in addition to significant enhancement of the bump postulated by Stellingwerf. Simon's plea for reexamination of the heavy element contribution to stellar opacity has been an inspiration for the OPAL (Iglesias *et al.* 1987) and the OP (Seaton 1993) projects. Inclusion of hitherto neglected transitions in heavy element ions resulted in large (up to factor 3) increase of opacities in the temperature range near $T \approx 2 \times 10^5 \text{K}$ leading to a pronounced bump, which is often referred to as the Fe-bump, because the transitions within the iron M-shell are the primary contributors.

Not long after the OPAL opacities became available for stellar modeling, first papers demonstrating that there are unstable modes in β Cep stars with periods consistent with observations were published (Cox *et al.* 1992; Kiriakidis *et al.* 1992; Moskalik & Dziembowski 1992). However, as pointed in the last paper, explanation of pulsation in lower luminosity β Cep required metallicity parameter $Z \geq 0.03$, which appeared too large even then. An improvement in atomic physics introduced in the subsequent release of the OPAL opacities (Rogers & Iglesias, 1992) removed this discrepancy. In the first models employing the new opacity data (Dziembowski & Pamyatnykh 1993; Gautschi & Saio 1993; Dziembowski *et al.* 1993) the instability was found already at $Z = 0.02$. Moreover, in addition to low-order p- and g-mode instability responsible for β Cep pulsation, an instability of high-order g-modes in a detached lower frequency range was found. In the β Cep domains instability was found only at high angular degrees ($\ell \geq 6$). However, for lower luminosity stars the instability extended to more easily detectable low degree modes and this provided a natural explanation of the origin of pulsation in Slowly Pulsating B (SPB) stars. This new type of variable stars was defined only two years earlier by Waelkens (1991).

Opacity mechanism in B stars

Not much was added after 1993 to our basic understanding how the opacity mechanism in massive B stars works. Plots which I show here in Figure 1 are very similar to those shown in Fig.1 of Dziembowski & Pamyatnykh (1993). The two envelope models selected for the plots correspond to an object in the mid of the β Cep domain in the H-R diagram and they differ only in the opacity data. Here, the newest versions of the data from the OPAL and OP projects were adopted. Shown in the upper panel, the run of the opacity coefficient, κ , reveals differences between the two data. The largest difference is seen at the inner side of the Fe-bump, which is centered at $\log T \approx 5.3$. Centered at $\log T \approx 4.6$, the bump caused by the HeII ionization plays no role in driving

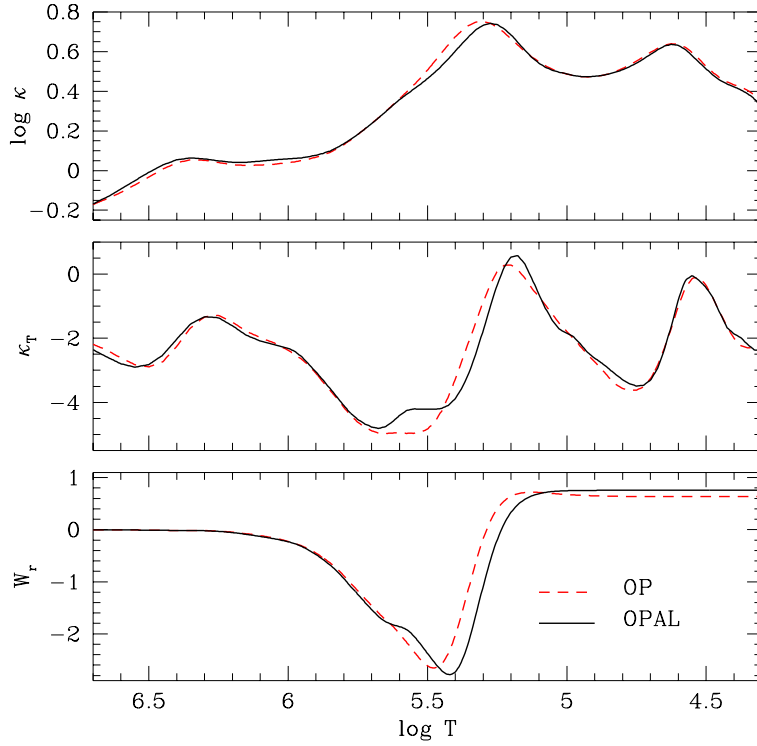


Figure 1: Panels from top to bottom show Rosseland mean opacity, κ , its logarithmic temperature derivative, κ_T , and the cumulative work integral for the fundamental radial mode, W_r , plotted against temperature in two stellar models. The models are characterized by the same parameters: $M = 9.63M_\odot$, $\log T_{\text{eff}} = 4.336$, $\log L = 3.891$, $X = 0.7$, $Z = 0.0185$, and the same heavy element mix (Asplund et al. 2005), but use different opacity data. Results obtained with the OPAL data (Iglesias & Rogers 1996) are shown with solid lines and those obtained with the OP data (Seaton 2005) are shown with dashed lines.

B star pulsation. The bump at $\log T \approx 6.4$, which is associated mainly with L-shell transitions and ultimate ionization of C, O, and Ne may be active in still hotter stars.

To understand how pulsation is driven, more helpful than the plot of opacity itself is the plot of its logarithmic temperature derivative at constant density, κ_T , which is depicted in the mid plot. The close connection of κ_T with mode excitation is seen when its run is compared with the run of the normalized cumulative work integral, W_r , which is shown in the bottom panel. The latter

describes the pulsation energy gain or loss by a mode per unit of time between the center and the distance r . An expression for W_r in terms of eigenfunction describing the Lagrangian perturbation of temperature and total flux, respectively, δT and δL , may be written as follows,

$$W_r = -\frac{1}{L} \int_0^r dr \oint dt \Re \left[\left(\frac{\delta T}{T} \right)^* \frac{d\delta L}{dr} \right] = \int_0^r dr \left| \frac{\delta T}{T} \right|^2 \frac{d\kappa_T}{dr} + \dots$$

where in the second equality, I wrote explicitly only the term giving rise to the opacity effect. This is just one of several terms arising from δL but it is the one that matters here. We may see in Figure 1 that in the driving zone, where W_r increases, κ_T increases too and the opposite is true in the damping zone. It is the slope of κ_T and not its value which is really relevant. In our models there are three driving slopes, but the only one active occurs in the thin layer extending $\log T \approx 5.5$ to 5.2 and is associated with the Fe-bump. The remaining two are inactive for different reasons. In the layer of the deep bump, the pulsation amplitude is very low while in the Hell-bump zone the thermal relaxation time, τ_r , is much shorter than the pulsation period, Π , so that the δL gradient cannot be maintained. All the damping arises in the layer of decreasing κ_T below the Fe-bump. In the considered cases, it is overcompensated by the driving above which renders the mode unstable.

The conditions for the mode instability are the same as for all opacity-driven pulsation. Within the zone of rising κ_T , the mode amplitude must be large and slowly varying with distance, so that the opacity perturbation dominates in the perturbed flux, and the thermal relaxation time is not significantly shorter than the pulsation period ($\tau_r \gtrsim \Pi$). Outside such a zone, the amplitude must be low or we must have $\tau_r \ll \Pi$. In B stars we encounter the opacity mechanism in the cleanest form. There is a convective layer in the Fe-bump zone of the early B-type stars but by far most of the flux is carried by radiation. The adiabatic temperature gradient changes within this zone but the variations are small, thus there is no significant role of the γ -mechanism.

In the two models considered, only one radial mode is unstable. At somewhat higher effective temperature, the first overtone is unstable, in addition to the fundamental. In our two models, the number of unstable nonradial modes is huge and the same is true for nearly all models of SPB and β Cep stars. The change in mode geometry does not change conditions for instability. The occurrence of the two instability ranges may be easily understood by considering changes in the shape of the radial eigenfunction describing Lagrangian perturbation of pressure, $y_p(r) \propto \delta p/p$, with period, Π , at specified degree, ℓ . For greater generality, it is better to consider changes with the dimensionless

frequency,

$$\sigma \equiv \frac{2\pi}{\Pi} \sqrt{\frac{R^3}{GM}}.$$

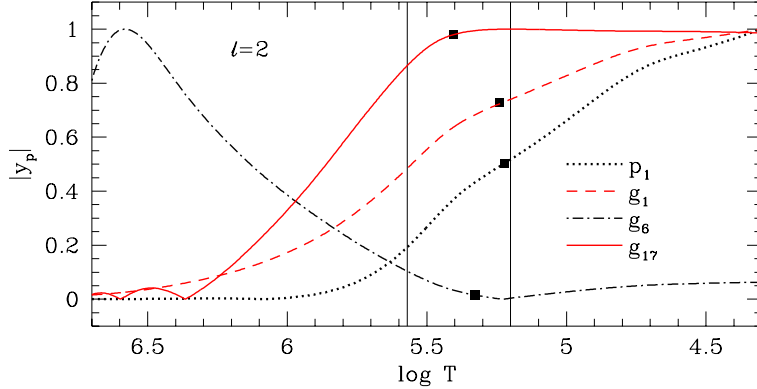


Figure 2: Absolute value of the eigenfunction describing Lagrangian pressure perturbation for selected quadrupole modes in the model calculated with the OP opacity data. The model parameters are given in the caption of Figure 1. Modes p_1 ($\Pi = 0.115$ d) and g_6 (0.529 d) are stable while modes g_1 (0.175 d) and g_{17} (1.376 d) are unstable. Dots in the curves indicate places where $\tau_r = \Pi$. The two vertical lines mark the boundaries of the driving slope associated with the Fe-bump.

Let us focus on the model employing the OP data. This is one of the seismic models considered for the β Cep star ν Eri (Dziembowski & Pamyatnykh 2008). Behavior of y_p in the outer layers for four selected quadrupole modes is shown in Figure 2. Mode p_1 has the period similar to first radial overtone and, like that, is stable. As long as $\ell \ll \sigma^2$, which is true in this case, the ℓ value has little effect on y_p in the outer layers. Mode g_1 has the shape of $y_p(r)$ and period suitable for driving. Unstable are also g_2 and g_3 modes. Periods of these three modes are in the range of 0.14 to 0.28 d, which is typical for β Cep stars. At $\ell = 1$ and ($3 \leq \ell \leq 8$) there are two or three unstable modes. Then the number decreases to 1 and at $\ell = 11$ the instability disappears.

In the intermediate frequency range ($\sigma \sim \sqrt{\ell}$), the absolute maximum of $|y_p|$ occurs below the Fe-bump. The mode g_6 in Figure 2 is an example. This mode is stable, though there is a significant destabilizing contribution arising at the driving slope of the deep bump but it compensates less than 60% of damping occurring below. The layers above $\log T = 6.3$ bring virtually no contribution to the total work integral. The $\ell = 2$ g-modes between $n = 5$ and $n = 13$ are stable. At still lower frequencies, the maximum is again close to

the surface and a new instability range may appear. All the $\ell = 2$ modes in the range $13 \leq n \leq 20$ are unstable. We may see in Figure 2 that the g_{17} mode has the shape y_p perfect for driving. Similar shapes are found for other degrees if $0.06 \lesssim \sigma^2/\ell \lesssim 0.3$, which implies shorter periods and higher radial orders at higher degrees. In our model, there are no unstable modes of this type at $\ell = 1$ because the $\tau_r \gtrsim \Pi$ condition is not well satisfied along the driving slope. The number of unstable modes increases up to $\ell = 24$ and the instability disappears at $\ell = 35$. With the m -dependence included, there is about 28 000 unstable high-order g-modes, which is nearly two orders of magnitude more than the low-order modes in this β Cep star model.

In the model calculated with the OPAL opacity data, the slow mode instability begins only at $\ell = 4$. This shift is connected with the upward shift of the Fe-bump (see Figure 1), hence lower τ_r within its range. Modes of lower ℓ s with suitable $y_p(r)$ have too long period to satisfy $\tau_r \gtrsim \Pi$ condition. To find instability with the OPAL data, we have to go to stars with lower L and/or T_{eff} where the Fe-bump occurs at higher density, hence at higher τ_r . This explains, as Pamyatnykh (1999) first noted, a significant difference between blue boundaries of the instability domains of low degree modes in the H-R diagrams calculated with OPAL and OP data. The latter place the boundaries, both of SPB and β Cep at a higher T_{eff} . Miglio et al. (2007), who used the new OP data (Seaton 2005) found difference in $\log T_{\text{eff}}$ reaching up to 0.05. The two domains partially overlap.

Question that remain to be answered

Are the current opacity calculations adequate?

The theory should account for excitation of all detected modes in the star and still it does not in all the cases. Particularly challenging are hybrid objects, where both high and low frequency modes are found. One such object is ν Eri. The difficulty with explaining excitation of modes at both ends of the observed frequency range were discussed by Pamyatnykh et al. (2004), who suggested that the iron abundance in the driving layer is significantly enhanced due to selective radiation pressure. The enhancement required to destabilize high frequency modes was somewhat less than factor 4 and somewhat larger for the low frequency mode. The authors based their proposal on the Charpinet et al. (1996) solution of driving problem for sdB pulsators. Unfortunately, they ignored work of Seaton (1999) from which it clearly follows that in massive B stars levitation leads to enhancement of the iron abundance not only in the bump zone but also in photosphere, and thus cannot be hidden.

We revisited the problem of mode excitation in ν Eri and in another hybrid

pulsator, 12 Lac, in our recent paper (Dziembowski & Pamyatnykh 2008). Since there is no spectroscopic evidence for chemical anomalies in any of these objects, we argued that levitation must be offset by a macroscopic mixing. We showed that even in the very slowly rotating ν Eri, mixing in outer layers by meridional circulation may be fast enough. With the OP opacities, there are unstable high- order g-modes $\ell = 2$ and their periods are in the 1.1 -1.6 d range in the ν Eri model. The observed periods are 1.6 and 2.3d. This might suggest that it is only a matter of further improvement in the opacity calculations to get the agreement. This is possible. However, in the case of 12 Lac, which is a brighter object, explanation of the long period (2.8 d), requires much larger opacity modification. Moreover, the use of the OP data did not help a bit in solving the difficulty with mode driving at the short period end. These discrepancies may justify a new plea to atomic physicists for revisiting opacity calculations.

How rotation affects driving

The effect of Coriolis force becomes significant as soon as the spin parameter, $s \equiv 2\Pi/\Pi_{\text{rot}}$, approaches one and, for the high-order g-modes, this happens well before the rotation rate approaches the maximum value. Modes cannot be described in spherical harmonics but within the *traditional approximation*, separation of the radial and angular dependencies in the pulsation amplitudes is still possible in terms of the *Hough functions*. Then, the Coriolis force effect is reduced to the replacement $\ell(\ell + 1) \rightarrow \lambda(s)$. The essence of the driving effect is not changed. The range of models having unstable low degree modes is somewhat increased (Townsend 2005). However, this approximation may be inadequate (Lee & Saio 1989). There are intriguing discoveries of a large number of modes in four Be stars with the *MOST* satellite and discrepant conclusions from model calculations regarding stability of these mode. (Cameron et al. 2008, and references therein). Accurate modeling of oscillations in these extreme rotators is still ahead of us. This is important because the detected modes may yield us the clue to understanding the Be star phenomenon.

What is the role of high-degree modes

A vast majority of the unstable modes are of high degree $\ell > 4$ and, thus, cannot be easily detected if their intrinsic pulsation amplitudes are similar to those of those low degrees. Smolec and Moskalik (2007) proposed that such modes play a role in collective saturation of the driving. This was their explanation why the amplitude they determined by nonlinear modeling of radial pulsation in β Cep stars were much higher than observed in any star of this type. They noted, however, that the postulated high- ℓ modes may be difficult to hide, as they

should contribute to spectral line broadening. According to my crude estimate, if saturation is mostly due to excitation of g-modes of high orders and degrees, then the r.m.s. velocity in the atmosphere should be between 50 and 100 km/s. This seems unacceptably high and, thus, we must conclude that the instability is not saturated. In such a case the terminal state of pulsation must be determined by a resonant excitation of damped modes. If all unstable modes had the same chances to grow, then the occurrence of detectable pulsation would have been regarded a miracle. The modes with $\ell \leq 2$ constitute only about 0.2 percent of the total population. Apparently, the coupling is more effective for high degree modes. Questions why it is so and what is the contribution of the invisible modes to spectral line broadening are awaiting answers.

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References

- Asplund M., Grevesse N., Sauval A.J. 2005, ASP Conf. Ser., Vol. 336, p. 25
 Cameron C., Saio H., Kuschnig R. et al. 2008, arXiv:0805.1720 (astro-ph)
 Chandrasekhar, S., Lebovitz, N. 1996, ApJ 136, 1105
 Charpinet S., Fontaine G., Brassard P., Dorman B., 1996, ApJ, 471, L103
 Cox, A. N., Morgan, S. M., Rogers, F. J., Iglesias, C. A. 1992, ApJ 393, 272
 Dziembowski, W. A., Pamyatnykh, A. A. 1993, MNRAS 262, 204
 Dziembowski, W. A., Pamyatnykh, A. A. 2008, MNRAS 385, 206
 Dziembowski, W. A., Moskalik, P., Pamyatnykh, A. A. 1993, MNRAS 265, 588
 Gautschi, A., Saio, H. 1993, MNRAS 262, 213
 Iglesias, C. A., Rogers, F.J. and Wilson, B. G. 1987, ApJ **322**, L24
 Iglesias, C. A., Rogers, F. J., Wilson, B. G. 1992, ApJ 397, 717
 Iglesias C. A., Rogers F. J. 1996, ApJ, 464, 943
 Kiriakidis, M., El Eid, M. F. and Glatzel, W. 1992, MNRAS 255, 1
 Ledoux, P. 1951, ApJ, 114, 373
 Lee U., Saio H. 1989, MNRAS, 237, 875
 Miglio A., Montalbán J., Dupret M.-A., 2007, MNRAS, 37, L21
 Pamyatnykh, A. A. 1999, Acta Astron., 49, 119
 Moskalik, P., Dziembowski, W. A. 1992, A&A 256, L5
 Pamyatnykh, A. A., Handler, G., Dziembowski, W. A. 2004, MNRAS 350, 1022
 Seaton, M. 1993, ASP Conf. Ser., Vol. 40, p. 222
 Seaton, M. 1999, MNRAS 307, 1008
 Seaton, M. 2005, MNRAS 362, L1
 Simon, N. R. 1982, ApJ 260, L87
 Smolec, R., Moskalik, P. 2007, MNRAS, 277, 645
 Stellingwerf, R. F. 1978, AJ, 83, 1184
 Townsend, R.H. D. 2005, MNRAS 360, 465
 Waelkens, C. 1991, A&A 246, 453